# A Distributed Localization Algorithm for Wireless Sensor Network Based on the Two-Hop Connection Relationship

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***Abstract*—Sensor's position is extremely crucial for the configuration and applications of wireless sensor network (WSN). In this paper, a novel range-free and distributed localization (THCRL) algorithm was proposed for WSN based on the two-hop connection relationship of a node. In THCRL algorithm, the information of one-hop and two-hop anchor nodes is firstly collected by an unknown node through broadcasting. Then, two regions, which are called as NSR and OCR, are computed when the collected information of anchors' position is viewed as geometric constraints. The NSR is a geometric constraint to the position of an unknown node that its two-hop anchor nodes should be out of its communication range. The OCR is another geometric constraint to the position of an unknown node that it should locate at the overlap of communication range of its one-hop anchor nodes. Finally, for each of unknown nodes, the overlap of NSR and OCR where it resides is determined through the method of grid search and the estimated position is obtained based on the grid with the highest score. Simulation results show that the THCRL algorithm has better performances on positioning precision, energy efficiency and robustness to irregularity of communication range, which can meet the requirements of node localization in WSN.**

***Index Terms*—range-free, distributed, wireless sensor network, geometric constraint, node localization**

## I. INTRODUCTION

Wireless Sensor Network (WSN) is defined as an ad hoc network consisting of a large number of dispersed sensor nodes, embedded computation, distributed information processing, and radio-link. The network distinguishes itself from other traditional wireless or wired networks through sensor and actuator based interaction with the environment. In recent years, sensor network begins to show its potential in many application fields such as transportation, military, biomedicine, emergency, etc [1, 2]. The inherent characteristics of these sensor networks make a node's location an important part of their state. Thus, how to determine the sensor's location becomes a topic of active research in wireless sensor network [3].

Many localization algorithms for sensor networks have been proposed to provide per-node position information. With regard to the mechanisms used for estimating location, these localization protocols can be divided into two categories: range-based localization algorithms and range-free localization algorithms. The former are defined by protocols that use absolute point-to-point distance estimate or angle estimates for calculating location such as Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Received Signal Strength Indicator (RSSI) [4-8]. Range-based localization algorithms terribly rely on precisely clock synchronization or extensive hardware that is usually expensive and of great energy consumption, which is not suit for low power and low cost application field. On the contrary, the later use only the connection relationships between nodes to implement coarse granularity localization without supporting of extra hardware, and the cost of communication is relatively small, so it has attracted great attention of researchers.

Connectivity information of neighbor nodes is the basis of range-free localization algorithm, and it is "one node is inside the communication range (CR) of the neighbor node", which forms the geometric constraint to the node's estimation position. Typical algorithms include Centroid algorithm [9], Convex Programming Localization algorithm [10], Smallest Enclosing Circle based Localization (SECL) algorithm [11], DRLS algorithm [12], DV-Hop algorithm [13, 14], Multidimensional Scaling-based (MDS) localization algorithm [15, 16] and so on. Both Convex Programming Localization algorithm and MDS-based localization algorithm are centralized algorithms, in which all the connectivity information of the whole network is collected by one node for further treatment. However, Centroid algorithm and SECL are distributed algorithms, in which each unknown node computed its position using the connectivity information of its neighbor anchor nodes that could be directly obtained. Generally speaking, centralized algorithm results in complex computation and more energy consumption, therefore, it doesn't suit for


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low-cost application of WSN. By contrast, because the distributed algorithm needs simple computation and less energy consumption, it is currently the most popular style and attracting considerable attention.

In order to improve the precision of the range-free localization algorithm, researchers have developed several technologies, which can estimate the distance without measuring the distance directly. DV-Hop algorithm uses the hop-count information to estimate the distance between sensor nodes. It works well for network with a dense, regular topology, but fails in sparse and irregular networks. At the same time, the process of DV-Hop can produce a heavy communication and generate a cumulative error. In addition, an approximate point-in-triangulation test (APIT) algorithm [17] was reported by T. He et al, which can provide high positioning accuracy even for an irregular network. However, the unknown node can't be located if there are fewer than three anchors within its communication range or there are three anchors but it doesn't reside within the defined triangular. DRLS algorithm uses a refinement step called vector-based refinement to obtain the high accuracy. But the message exchanging cost greatly increases. In a word, most of the existed range-free localization algorithms are lacking in general applicability due to the following reasons: (1) without meeting the requirements of WSN including decentralization, scalability and resource efficiency; (2) without considering the effects of environment. Therefore, it is necessary to develop new localization scheme for WSN.

Usually, range-free localization algorithms mainly use the connectivity information as the geometric constraints. However, the non-connectivity information between nodes is also the geometric constraint to node's position [18], which is helpful for improvement of localization precision. Based on two kinds of geometric constraints extracted from the one-hop and two-hop neighbor relationship, a novel distributed range-free algorithm called as THCRL (two-hop connection relationship-based localization) is proposed in this paper. According to the non-connectivity information, one geometric constraint confines the unknown node in a region (denoted as NSR, neighbor-split region) where the neighbor nodes can be split into one-hop neighbor nodes and multi-hop neighbor nodes in terms of its CR. The other also confines the unknown node in a region (denoted as OCR, overlap of CRs) which is the overlap of communication range of its one-hop neighbor nodes. Through a grid search method on the overlap of NSR and OCR, the position of unknown node can be found.

The remainder of the paper is organized as follows: Section 2 describes the network model of THCRL. Section 3 gives detailed descriptions of the algorithm of our work. Section 4 describes our simulation results. Finally, we conclude in Section 5.

## II. Network Model

There are two kinds of sensor nodes in the network: anchor nodes and unknown nodes. Suppose that P unknown nodes and Q anchor nodes are randomly deployed in a flat area. The positions of all nodes are modeled as a vector $X = (x_1, x_2, \cdots, x_{P+Q})$ and the distance between node i and j is defined as

$$d(i, j) = \left\| x_i - x_j \right\|, \tag{1}$$

where $\|\cdot\|$ denotes the Euclidean distance. Additionally, the network is assumed to have the following properties:

(1) Each sensor node is fixed and equipped with an omnidirectional antenna, which has the identical hardware configuration and function of power control.

(2) Each sensor has a unique identifier (ID).

(3) The environment where sensor nodes are deployed is similar.

(4) The anchor nodes are position aware.

(5) The maximum communication radius of sensor is *R*.

(6) For a unknown node (N), three are two kinds of anchor nodes in the network as shown in Fig. 1. One is the one-hop anchor nodes such as C2, which can directly communicate with node N. The other is the multi-hop anchor node M with the distance d(N, M) larger than *R* such as C1, which can not directly communicate with node N.

## III. The THCRL Algorithm

As shown in Fig. 1, if node N can detect the anchor nodes C1 and C2, it also can get some geometric constraints to its position. For example, node N must locate within the maximum communication range of C2 and outside the maximum communication range of C1. If more geometric constraints can be found, node N must be able to accurately calculate its position. In THCRL algorithm, unknown nodes collect the information of neighbor anchor nodes through message exchanging, and then extract the geometric constraints from these information to obtain the positions. With a view to the energy consumption and memory capacity of sensor node, the geometric constraints of one-hop anchor nodes and two-hop anchor nodes are taken into account in this algorithm. Basically, the THCRL algorithm has the following six steps coupled with the two-hop flooding:

***step1***: Each anchor node broadcasts its position only once.

***step2***: Each node (including all unknown nodes and all anchor nodes) listens the network and collect the information of its one-hop anchor nodes.

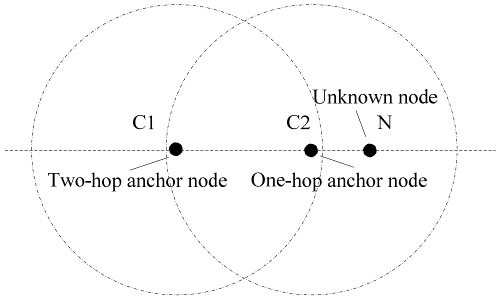


Figure 1. Two kinds of neighbor anchor nodes in the network.

***step3***: Each node broadcasts the information of its one-hop anchor nodes only once.

***step4***: Each unknown node collects the information of its one-hop anchor nodes and two-hop anchor nodes.

***step5***: Based on the positions of its one-hop anchor nodes and two-hop anchor nodes, each unknown node calculates the NSR and OCR.

***step6***: Based on the overlap of NSR and OCR, a search region and the corresponding grid score table are built. Through a grid voting process, each unknown node can determine its position by using the coordinates of grids with the highest score.

### *A. The Method for NSR Computation*

For any position-unknown node N, two sets are defined: Set S1 is composed of one-hop anchor nodes and set S2 is composed of two-hop anchor nodes. Meanwhile, a circular area, whose radius is equal to the maximum communication radius *R*, is denoted as the predefined circular area (PCA) in THCRL algorithm. When node N is within PCA, all anchor nodes are divided into inner anchor nodes and outer anchor nodes, which are defined as set D1 and set D2, respectively.

If the center of PCA is just the true position of node N, S1 equals to D1, and S2 is included in D2. Otherwise, if the center of the circular area deviates from the true position of N, there would be a mismatch between S1 and D1, and between S2 and D2 as shown in Fig. 2. It can be seen that D1 includes both two-hop anchor nodes and one-hop anchor nodes.

The PCA with different center points would result in various mismatches. In order to quantitatively describe these mismatches, a mismatch function of an anchor node is defined as

$$m_{1,s}^{(c)} = \begin{cases} 0 & ,if \quad d(c,s) \le R \\ 1 & ,if \quad d(c,s) > R \end{cases} \tag{2}$$

and

$$m_{2,t}^{(c)} = \begin{cases} 1 & ,if \quad d(c,t) \le R \\ 0 & ,if \quad d(c,t) > R \end{cases}, \tag{3}$$

where $s \in S1$ , $t \in S2$ and $c$ is the center of the corresponding PCA. For a certain PCA where node N resides, the summation of the two mismatch functions above is defined as its mismatch function as following:

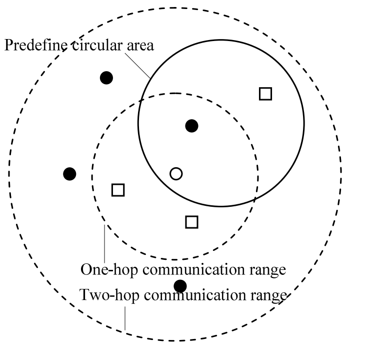


Figure 2. A mismatch occurs in the network.

$$T_c = \sum_{s\in S1} m_{1,s}^{(c)} + \sum_{t\in S2} m_{1,t}^{(c)} . \tag{4}$$

If there are enough anchor nodes near unknown node N, the mismatch function T is equal to 0 when the center of PCA coincides with or is very close to its true position. Otherwise, the further the distance between the center of PCA and the true position of node N is, the greater the value of the mismatch function C is. In other words, this mismatch function C gives a geometric constraint to the estimated position of unknown node N. All the center points of PCA, whose mismatch function is equal to 0, compose the NSR of node N. That is

$$NSR = \{c \mid T_c = 0\} . \tag{5}$$

In ideal conditions, the NSR is the same as the overlap of washers, which is the circular area with a radius of 2×*R* minus the circular area with a radius of *R* centered at the position of the two-hop anchor nodes. However, if a two-hop anchor node is viewed as a one-hop anchor node by mistake, the overlap region of these washers doesn't exist. In this situation, Equation (5) can be corrected as

$$NSR = \{c \mid \forall C1, T_c \le T_{c1}\} . \tag{6}$$

### *B. The Method for OCR Computation*

For any position-unknown node N, the set S1 is easily determined through direct communication. That is to say that the maximum communication range of one-hop anchor nodes can bring another geometric constraint to the estimated position of node N, indicating that the position of node N has to locate at the overlap of CRs of its one-hop anchor nodes. If the OCR of node N can be computed, its position also can be bounded.

Usually, the OCR is composed of several circular arcs. Consequently, if the intersection points of these circular arcs can be determined, the OCR can be obtained as shown in Fig. 3. Here, the method for finding the corresponding circular arcs of OCR can be summarized as [19]:

***step1***: Finding all the intersection points of CRs for each pair anchor nodes in set S1.

***step2***: For each CR, order the intersection points in a counter-clockwise direction. For each intersection point, label that point "+" if the segment from that point in the positive direction lies in both CRs meeting at that point, and label "-" otherwise. In Fig. 3(a), it is clear that the intersection points of circle C5 should be denoted as $P^{+}_{54}$, $P^{-}_{51}$, $P^{+}_{53}$, $P^{-}_{54}$, $P^{+}_{52}$, $P^{-}_{53}$, $P^{+}_{51}$ and $P^{-}_{52}$.

***step3***: For each CR, traverse the circle in a positive-angle direction until a "+" is followed immediately by a "-". Those two points, which is called as "+-" pair, are the corner points of OCR. If there are two or more such "+-" pairs, then it is concluded that no corner points of OCR exits in this circle. In Fig. 3(a), the order of intersection points of *C1* is $\rightarrow P^{+}_{12}\ P^{-}_{14}\ P^{-}_{13}\ P^{-}_{15}\ P^{-}_{12} P^{+}_{14}\ P^{+}_{15}\ P^{+}_{13} \rightarrow$, indicating that $P^{+}_{12}$ and $P^{-}_{14}$ are the corner points of OCR. On the contrary, the order of intersection points of *C5* is $\rightarrow P^{+}_{51} P^{-}_{52}\ P^{+}_{54}\ P^{-}_{51}\ P^{+}_{53}\ P^{-}_{54}\ P^{+}_{52}\ P^{-}_{53} \rightarrow$, indicating that

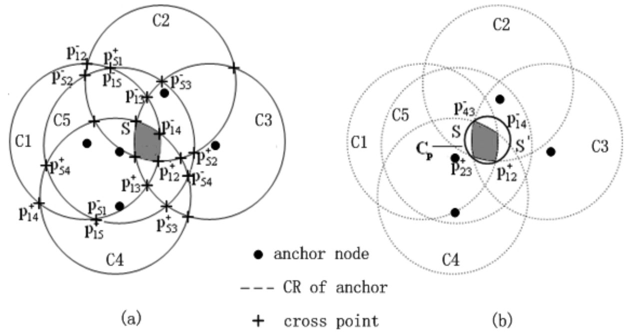

Figure 3. The process for computation OCR.

there are four "+-" pairs and no corner point of OCR exists.

***step4***: Doing *step3* for CRs of all anchor nodes in set S1, and finding all the corner points. In Fig. 3(a), the corner points are $P^{-}_{43}$ $P^{+}_{23}$ $P^{+}_{12}$ $P^{-}_{14}$ as shown in Fig. 3(b).

***step5***: Because the OCR is generally irregular, we try to find other regular graph to bound the position of node *N*. Based on Meggido's linear programming algorithm [20], node N calculates the smallest circle $C_p$ which contains all of the corner points. As observed in Fig. 3(b), node *N* has to be located within the circular region $C_p$.

Through these calculations, the position of node N can be bounded in the smallest circular region for further process.

### C. The Optimization Algorithm for Sensor's Position

So far, the estimated position of unknown node N must locate within the overlap of NSR and OCR. Since the overlapping region is generally irregular graph, it would be computationally expensive to analytically determine the node's position. So a method of grid search is used. Unknown node N divides the smallest circle Cp into grids and keeps a score for every grid in a grid score table as shown in Fig. 4. The search algorithm has three steps:

***step1***: Node N splits the smallest circle $C_p$ into grids according to the search granularity $\delta$. Here, the search granularity is equal to the edge length of a grid.

***step2***: Initially, all grids have a zero score in grid score table. For each grid, node N checks to see whether it lies in NSR or OCR. If any grid passes this check, node N increases its score by one. If not, its score doesn't change. This process is repeated for each grid. It can be seen from Fig. 4 that the overlapping region of NSR and OCR is determined by the grids whose score equals to 2 in the grid score table.

***step3***: Node N determines its position as the centroid of the grid points with the score of 2, and then the search algorithm ends.

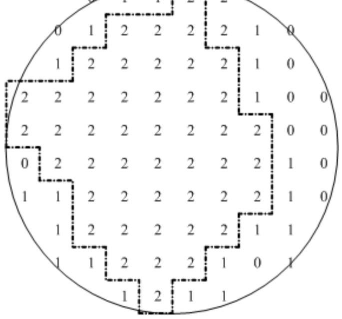
Figure 4. The grid search process for estimating the node's position

### D. The Position Optimization under Real Environment

Due to the properties of device and the propagation media, the communication range of a node is usually not an ideal circle. In order to imitate the real environment, the irregular radio model proposed in [21] is adopted. In this model, propagation range of node changes with variation of propagation angle between an upper limit ($R_U$) and a lower limit ($R_L$). Parameter *DOI* controls the variation of communication range. As shown in Fig. 5, the larger the *DOI* is, the more irregular the radio model is. If *DOI* equals to 0, the communication range of a node is constantly equal to *R*.

When this radio model is adopted, two cases appear as follows:

***Case1***: Due to the irregularity of radio model, two nodes ($N_1$ and $N_2$) may be viewed as two-hop neighbor nodes although $d(N_1, N_2)$ is smaller than *R*.

***Case2***: During the process of grid search, there may be no grid whose score is equal to 2 in the grid score table.

For *Case1*, this mistake can decrease the range of NSR, leading to that the overlap of NSR and OCR does not exist or all the scores of grids are less than 2. In other words, *Case2* may result from *Case1*. In this situation, unknown node N should calculate its position as the centroid of the grid points with the highest score. In addition, if all the scores of grids are 0, node N should determine its position as the center of the smallest circle $C_p$.

## IV. PERFORMANCE EVALUATIONS

### A. System and performance parameters

In our simulations, THCRL algorithm was executed on a scenario using OMnet++ 4.0 and Matlab 6.5, where 200 unknown nodes and some anchors are randomly deployed inside a $10r\times10r$ square. To evaluate the performance of THCRL, the system parameters need to be determined and the performance parameters need to be defined. The ones used in simulations are listed below:

(1) To ensure that the network is connected, the starting *R* for simulations is $0.5r$ with the corresponding average connectivity 1.57 at least.

(2) The rate of localized nodes, *RLN*, is defined as where $N_{success}$ is the number of unknown node which is

$$RLN = N_{success} / P \times 100\% \qquad (7)$$

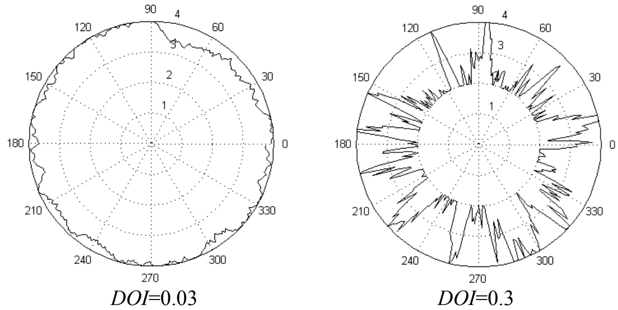

Figure 5. The radio model with *DOI*=0.03 and *DOI*=0.3, respectively.

successfully localized.

(3) The average localization error, *ALE*, is defined as

$$ALE = \sum_{i=1}^{N} \left\| X_{est,i} - X_{real,i} \right\| / (P \times r) \qquad (8)$$

where $X_{est,i}$ is the estimation position of node i, $X_{real,i}$ is the true position of node i.

*B. Results of simulations and analysis*

The maximum communication radius *R* and the number of anchor nodes *Q* are closely related to the parameter *RLN*. In network, if more anchor nodes are deployed or the transmission power of node is enhanced, the average number of one-hop anchor nodes and two-hop anchor nodes obtained by an unknown node will increase. Therefore, the *RLN* has to increase with the values of *Q* and *R*. As shown in Fig. 6, when the number of anchor nodes is larger than 125 and *R* is larger than 1.25*r*, almost all the unknown nodes can be successfully localized. However, when the *R* is smaller than 0.5*r*, the *RLN* of network is only 44.6% although the number of anchor nodes exceeds the number of unknown nodes. Moreover, the *RLN* of network almost drops down to 0% when the number of anchor nodes is smaller than 25 and *R* is smaller than 0.5*r*.

Fig. 7 shows the position estimation accuracy of THCRL algorithm as a function of *R* when the number of anchors is 125, *DOI* is equal to 0 and the search granularity *δ* is 0.01*r*. The range of *R* is from 1.25*r* to 3.5*r*, which lead to the average connectivity from 14.9 to 124.0. It seems that the localization error of SECL algorithm is much greater than that of Centroid algorithm when *R* is smaller than 1.75*r*. For all the *R*s, the results of THCRL algorithm outperform those of other algorithms. Especially, the *ALE* curve of THCRL algorithm is much lower than the one of DRLS algorithm, implying that the application of two geometric constraints is more feasibly preferable than the vector-based refinement technique in improving the performance of range-free localization algorithms. It should be particularly noted that the curve of THCRL quickly descends and then even tend to be flat with the increase of *R*. When the *R* is larger than 2.75*r*, the *ALE* is lower than 0.05*r* and is very close to the value of *δ*. Although radio radius larger than 2.75*r* can lead

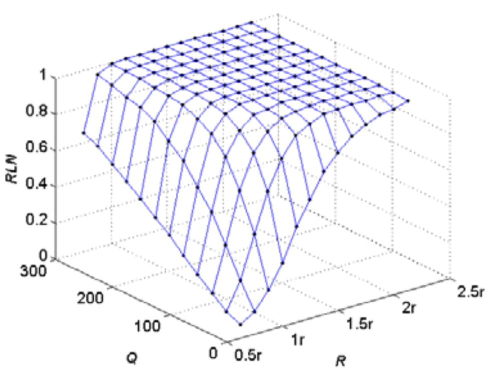


Figure 6. The *RLN* changes with the communication radius *R* and the number of anchor nodes *Q*.

to better result, the improvement margin is small and the communication consumption would increase greatly.

To evaluate the effects of anchor nodes on *ALE*, the results for varying the number of anchor nodes are depicted in Fig. 8. Because the increase in the proportion of the anchor node causes an increase in the amount of information of the anchor nodes, position estimation accuracy of all algorithms increases. When the number of anchor is larger than 175, the *ALE* of SECL algorithm is very close to that of Centroid algorithm. This is because that the centroid point is in close proximity to the center of the smallest enclosing circle provided enough anchor nodes are deployed. For all *M*s, THCRL algorithm has the best performance among all three algorithms. This behavior is mainly due to the fact that the gradual increase in number of anchor nodes could gradually decrease the range of NSR and OCR, as well as the overlap of NSR and OCR, which leads to the better performance in the process of grid search. It should also be noted that the improvement on *ALE* of THCRL algorithm is unobvious when the number of anchor nodes is above 250. This is due to that the corresponding localization error is much close to the value of *δ*.

The sensitivity of *ALE* to *DOI* is a major concern for range-free-based localization algorithm. Fig. 9 shows the effects of increasing of *DOI* on *ALE* when *R* is 1.5*r* with 150 anchor nodes in network. Here, the $R_L$ is *R*/2 in all directions. It can be seen that the localization accuracy consistently degrades as the range error gradually increases except the Centroid algorithm. When the *DOI* ranges from 0 to 0.3, the *ALE* of the Centroid algorithm almost keeps invariant because the centroid of one-hop anchor nodes is simply taken as the estimated position. When the value of *DOI* is larger than 0.25, the performances of Centroid algorithm and THCRL algorithm are very similar. This is attributed to that more and more one-hop anchor nodes may be viewed as the two-hop anchor nodes, which results in that the number of correct grids in search step becomes smaller with the increasing of *DOI*. Additionally, DRLS algorithm has poor performance in the presence of radio irregularity, indicating that the strategy of THCRL algorithm is more applicable than the refinement strategy.

Fig. 10 shows the performance of THCRL algorithm as a function of search granularity δ with *R*=1.5*r* and *Q*=150. It should be noted that the error of localization gradually increase with the increase of δ. This behavior is explained by the fact that the region of overlap of NSR and OCR can be precisely shaped when the grid with smaller size is used. Thus, a balance should be made between the localization precision and memory consumption.

In the process of localization, the energy consumption is dominated by the communication cost. Here, the number of data packet (*NDP*) during localization is used for analysis of communication cost. In Centroid algorithm and SECL algorithm, only the anchor nodes broadcast its information in the network, meaning that the number of data packet is *Q*. However, both the unknown nodes and anchor nodes should broadcast their information in THCRL algorithm DRLS algorithm. The

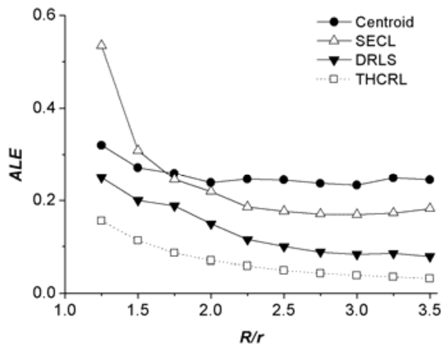

Figure 7. *ALE* changes with *R* when the number of anchors is 125 and *DOI* is 0.

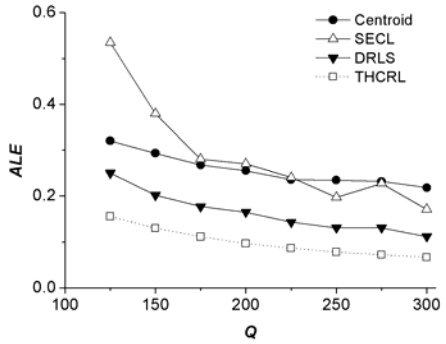

Figure 8. *ALE* changes with the number of anchors when *R* is 1.25*r* and *DOI* is 0.

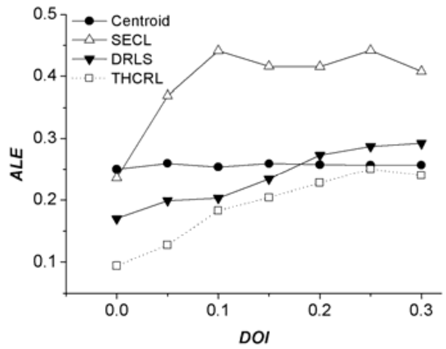

Figure 9. The effects of *DOI* on ALE when *R* is 1.5*r* with 150 anchor nodes in network.

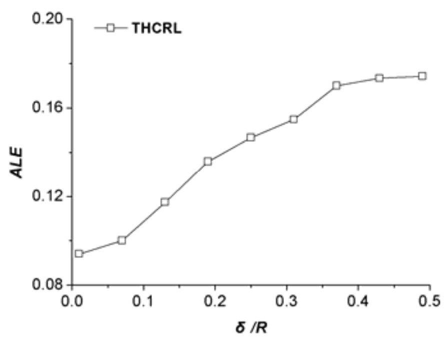

Figure 10. ALE of THCRL algorithm changes with search granularity δ when *R*=1.5*r*, *Q*=150 and *DOI*=0.

value of parameter *NDP* of these algorithms is depicted in Fig. 11 and Fig. 12. It can be seen that the communication cost of THCRL algorithm and DRLS algorithm increases rapidly as the increase of the number of anchor nodes or communication radius because the increase in the network density rapidly increases the number of sensor nodes existing within a one-hop distance from a sensor node. Moreover, DRLS algorithm

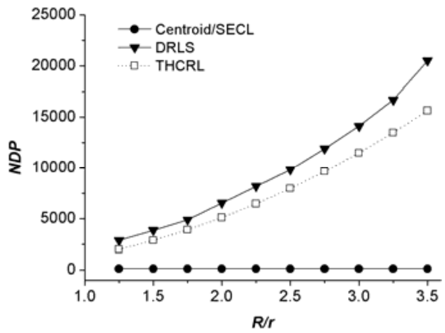

Figure 11. The communication cost changes with *R* when *Q*=125 and DOI=0.

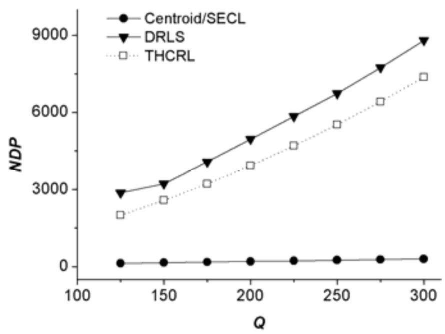

Figure 12. The communication cost changes with *Q* when *R*=1.25*r* and *DOI*=0.

transmits more data packets compared to THCRL algorithm due to that the former performs additional broadcasting in addition to two-hop flooding to provide information of the anchor nodes to the unknown nodes. However, the localization error of the latter is much lower, indicating that it has high energy efficiency. Additionally, it is also can be concluded that the communication radius and the number of anchor nodes should decrease for energy saving under the premise of meeting the requirement of localization precision.

## V. Conclusions

This paper described a novel distributed localization algorithm based the two-hop connection relationship. In this algorithm, the information of one-hop and two-hop neighbor anchor nodes is sufficiently used to confine the position of an unknown node in the overlap of NSR and OCR where it resides. Through the grid search on this region, its estimated position is obtained based on the grid with the highest scores. Simulation results show that the THCRL algorithm can provide high localization precision with lower communication load. Moreover, this algorithm has the better performance on robustness to the irregularity of communication range, indicating that it is applicable in practical application of WSN.

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